LA-UR-21-24383
Approved for public release; distribution is unlimited.

Title: "The Princess and the pRad"

Author(s): Sjue, Sky K.

Intended for: Physics Cafe presentation to P Division

Issued: 2021-05-06

"The Princess and the pRad"

Sky Sjue

Physics Café, Physics Division, LANL

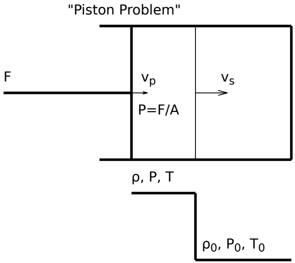
6 May 2021

This is an aspirational sketch of a pRad EoS platform

- There might be a way to measure Hugoniot curves to very high pressures (100 Mbar?) at LANSCE using proton radiography (pRad) one of these years.
- There are technical problems to be solved.
- But we also demonstrate a solution to one of the technical issues.
- We cover ground that is germane at LANL but possibly not familiar to some Physics Division personnel.

Shock physics and jump conditions

For our purposes, a strong shock is a discontinuity propagating through a homogeneous material at a supersonic speed.



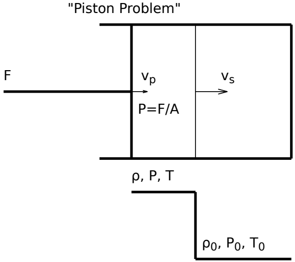
Conservation of Mass
need $M_{in} = M_{out}$,
$Av_s \Delta t \rho_0 = A(v_s - v_p)\Delta t \rho$,
and $v_s \rho_0 = (v_s - v_p)\rho$
Or, $v_p = v_s(1 - \rho_0/\rho)$

Impulse
$PA\Delta t = (Av_s \Delta t \rho_0)v_p$,
so $P = \rho_0 v_s v_p$
Or, $P = \rho_0 v_s^2 (1 - \rho_0/\rho)$

$P = \rho_0 v_s v_p$ gives pressure from velocity measurements.
$P = \rho_0 v_s^2 (1 - \rho_0/\rho)$ can give pressure from radiography.

Energy jump and ideal gas limit

Find strong shock limit on density jump for an ideal gas.



Work done by piston

$$PA(v_p\Delta t) = A(v_s - v_p)\Delta t \rho e + A(v_s - v_p)\Delta t \rho v_p^2/2$$

We can rewrite using mass and impulse conditions as $\rho e = \rho v_p^2/2$.

$$\rho e/P = (\rho/\rho_0)(v_p/v_s)/2 = (\rho/\rho_0)(1-\rho_0/\rho)/2 = (\rho/\rho_0 - 1)/2$$

$$\rho/\rho_0 = 2\rho e/P + 1$$

Ideal gas EoS is $P = \rho e(\gamma - 1)$ where $\gamma = C_p/C_v$.

$\rho/\rho_0 = \dfrac{\gamma+1}{\gamma-1}$ in this limit is 4 for monatomic gas, 6 for diatomic gas.

EoS based on gas guns

This is a venerable technique still being widely practiced – first search result from "gas gun equation of state"

JOURNAL OF APPLIED PHYSICS VOLUME 37, NUMBER 9 AUGUST 1966

Measurement of the Very-High-Pressure Properties of Materials using a Light-Gas Gun

A. H. JONES, W. M. ISBELL, AND C. J. MAIDEN
General Motors Defense Research Laboratories, Santa Barbara, California
(Received 9 December 1965; in final form 14 March 1966)

Equation-of-state data at extremely high pressure is required for the analysis of many problems pertaining to physics, geophysics, astrophysics, etc. The conventional method used to obtain such data is to impact

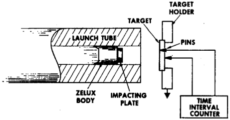


FIG. 1. Principle of technique.

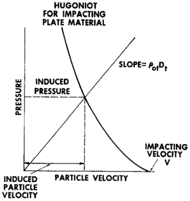
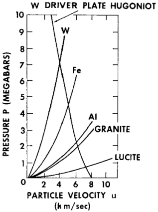


FIG. 2. "Impedance match" solution for equation of state.

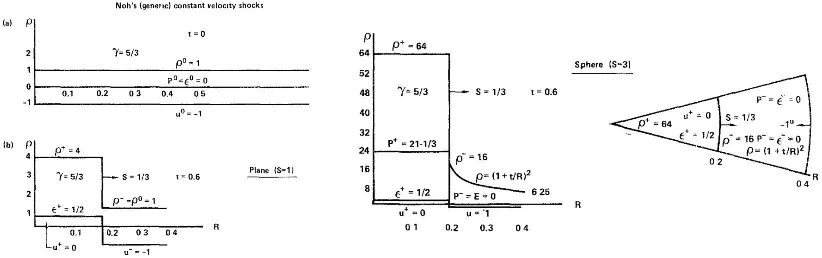


With modified instrumentation, still the state of the art. Has 1D advantages, but also subject to 1D limitations.

Radiography: no impedance matching! Just measure ρ and v_s.

The blessing of dimensions

In pursuit of high pressure, more dimensions do not curse us! This is Noh's test problem. There are simple solutions to the Euler equations with the initial condition of a material moving toward the origin with constant velocity in 1, 2 or 3 dimensions.



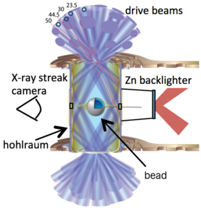
In 1D (like a flyer plate), shocked density is $(\gamma+1)/(\gamma-1) = 4$ and pressure is $P = 4/3$.
In 3D, shocked density is $(\gamma+1)^3/(\gamma-1)^3 = 64$ and pressure is $P = 64/3$!

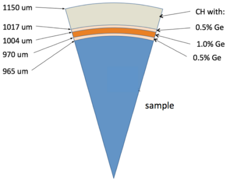
To harness the power of added dimensions, we need radiography!

"Errors for calculations of strong shocks using an artificial viscosity and an artificial heat flux," W.F. Noh, *J. Comp. Phys.* **72** 78–120, 1987

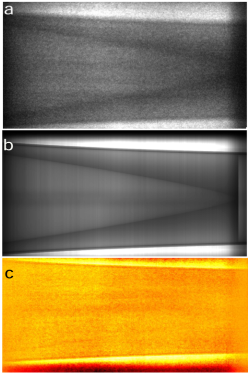
The Gigabar NIF experiment

The Gigabar experiment at the National Ignition Facility measures states to very high pressures, but can only do it for low Z materials.

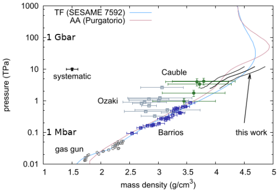




Gbar CH target/sample for ingoing spherical shock
X ray image is taken with streak camera of a strip across the center of the sphere



a: data, b: model, c: residual
time is horizontal, radius is vertical



Nominal CH density is 1.05 g/cc, so the maximum value on this plot is close to monatomic ideal gas value $\rho/\rho_0 = (\gamma+1)/(\gamma-1) = 4$.

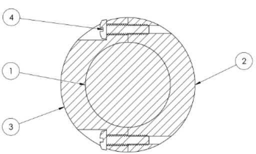
Main point is that this technique reaches noticeably higher pressures than other techniques on a logarithmic scale!

"Absolute Hugoniot measurements from a spherically convergent shock using x-ray radigraphy," Damian Swift et al., *Rev. Sci Inst.* **89**, 053505 (2018)

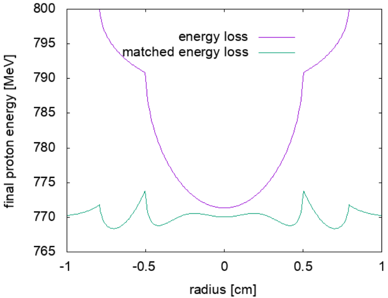
Pea size at pRad

We can measure through high Z materials at pRad if we make them about the size of a pea. Quality imaging of such a geometry is necessary (if not sufficient) for high pressure EoS data.

ITEM NO.	PART NUMBER	QTY.
1	AU CENTER	1
2	Ti OUTER SHELL THREADED	1
3	Ti OUTER SHELL	1
4	SCREW, CH HEAD, M1.2 X .025mm X 5mm LENGTH, 316 SST	2



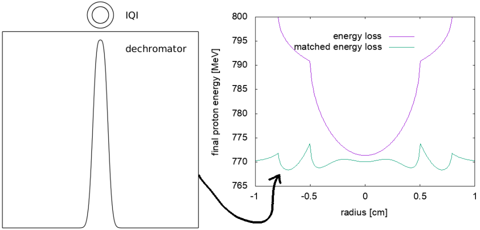
This is a 1 cm diameter sphere of gold surrounded by a spherical shell of titanium alloy.

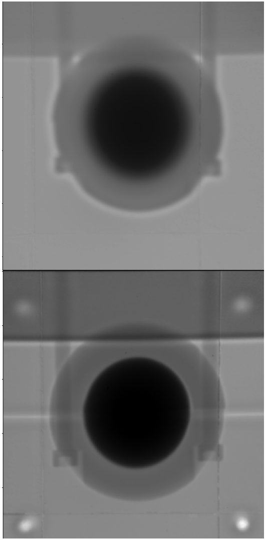


The energy loss through the bare sphere is a problem for pRad image quality.

The princess at pRad would be the chromatic aberrations of the magnetic lens. They are quite sensitive to a piece of gold the size of a pea.

We have demonstrated a solution to the energy mismatch





This was designed and fielded during the pandemic!
The top pRad image is unmatched, the bottom image is matched.
This was our first iteration and we have an improved dechromator in the works.

see "Image quality indicator...,", Sjue et al., LA-UR-20-26337